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Review

Real-time sensors for indoor air monitoring and challenges ahead in deploying them to urban buildings

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Graphical abstract

Research highlights

- State of the art on air pollution sensing in indoor environments is reviewed
- Technology for indoor air sensing has notably progressed, albeit challenges remain
- Awareness of, and regulation for, IAQ are lagging behind the technology
- Therefore the emerging IAQ sensing technologies appear ahead of their time

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Abstract

Household air pollution is ranked the 9th largest Global Burden of Disease risk (Forouzanfar et al., The Lancet 2015). People, particularly urban dwellers, typically spend over 90% of their daily time indoors, where levels of air pollution often surpass those of outdoor environments. Indoor air quality (IAQ) standards and approaches for assessment and control of indoor air require measurements of pollutant concentrations and thermal comfort using conventional instruments. However, the outcomes of such measurements are usually averages over long integrated time periods, which become available after the exposure has already occurred. Moreover, conventional monitoring is generally incapable of addressing temporal and spatial heterogeneity of indoor air pollution, or providing information on peak exposures that occur when specific indoor sources are in operation. This article provides a review of the new air pollution sensing methods to determine IAQ and discusses how real-time sensing could bring a paradigm shift in controlling the concentration of key air pollutants in billions of urban houses worldwide. However, we also show that besides the opportunities, challenges still remain in terms of maturing technologies, or data mining and their interpretation. Moreover, we discuss further research and essential development needed to close gaps between what is available today and needed tomorrow. In particular, we demonstrate that awareness of IAQ risks and availability of appropriate regulation are lagging behind the technologies.

Keywords: *Indoor air quality; Air quality sensing; Gas sensors; Urban buildings; Human exposure; Low cost instrument*

1. Introduction

Indoor air quality (IAQ) is a growing concern in both the developing and developed world. The World Health Organisation linked 4.3 million deaths globally in 2012 to household cooking using coal, wood and biomass stoves, compared with 3.7 million deaths

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for outdoor air pollution. Most recent assessments have placed indoor air pollution as the 9th largest Global Burden of Disease risk (Forouzanfar et al., 2015). IAQ is affected by household-generated emissions of gaseous species, including volatile organic compounds (VOCs), particle matter (PM) of diverse size ranges (Heal et al., 2012) and microbial contaminants including bacteria, viruses and fungi. These pollutants deteriorate IAQ and have subsequent effects on human health. Another factor of significance to human wellbeing in indoor environments is thermal comfort; temperature and indoor air pollution are often interrelated and governed by ventilation. Mounting evidence links poor IAQ and thermal comfort with reduced human productivity and dissatisfaction in adults (Wyon, 2014), adverse impacts on the learning ability of school children (Wargocki and Wyon, 2013), and the growth of bacterial and fungal staining (blackening) on the building's interior walls and roofs (Kumar and Imam, 2013). Infiltration of outdoor air to indoor environment is another key factor affecting IAQ. This infiltration depends on the type and operation of the building ventilation system (natural or mechanical), as well as outdoor concentrations of the pollutants, which vary, and display heterogeneity and intra-city differences in pollutant concentrations (Kumar et al., 2013a; Zhou et al., 2013). Consequently indoor concentrations of both gases and PM, in the absence of indoor sources often show similar trends to outdoor environments, particularly in naturally ventilated buildings, and therefore can be estimated from the outdoor concentrations (Jones et al., 2000; Kumar and Morawska, 2013).

The primary methods to improve IAQ levels in most buildings is to control the indoor sources and building ventilation to dilute or remove indoor generated pollutants (Kumar et al., 2016). However, such methods are not aimed to apportion contributions from the individual indoor sources, or characterise peak concentrations. A number of conventional instruments are available for monitoring PM and gaseous pollutants to determine the IAQ but most of them have practical and technical limitations preventing them from being deployed in sufficiently large numbers in different parts of a house. These instruments also are expensive and incapable of providing high resolution spatio-temporal data, which is important for quantifying the peak exposure levels and identifying the key sources responsible for indoor air pollution, in order to design and implement mitigation strategies. In this context, a need

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for real-time gas and PM sensors for assessing IAQ is recognised, and their availability could potentially change the ways IAQ is managed. However, it is important to understand how indoor sensing differs from outdoor (Kumar et al., 2015) and what the unique challenges indoor environments present for IAQ sensing.

The first key feature required of IAQ sensing is low unit cost of sensor kits or systems (i.e., a network of sensor kits). This is often the case for both indoor and outdoor sensing technologies (Kumar et al., 2016; Kumar et al., 2015), however, the requirement that IAQ sensors are capable of detecting sufficiently low concentration levels of pollutants is more difficult. When these sensors are operated with batteries, they should be long-lived so that there is no need for their frequent replacement or to connect them to multiple power points within a building. Size is another factor, and ideally they should be miniaturised so that they can be distributed across the building discreetly without taking up too much space or disturbing people in residential and public buildings. And finally, they should be silent, in order to be accepted by the building occupants.

A further question is how realistic is it to deploy sensors for IAQ assessments. Many types of sensors have been used to measure air pollutants concentrations (Kumar et al., 2015), particularly for industrial applications and for vehicle emission monitoring, however, in both these cases the concentrations are high in the order of ppm compared to those found in indoor environments (IAQ EU Directives, 1989; WHO, 2010). As a result, the first challenge is to make these sensors more sensitive to low concentration levels. In doing so, however, we would run into problems of selectivity (i.e., there are many compounds in the air at low concentrations, which the sensors would detect, and give the similar response as to the compound we want to measure).

A number of review articles focuses on IAQ (Morawska et al., 2013; Luengas et al., 2015), outdoor air pollution sensing (Castell et al., 2014; Kumar et al., 2015), gaseous sensors (Xin et al., 2015) or health effects (Lim et al., 2012; Smith et al., 2000). However, none of them have addressed the potential value of continuous air pollution sensing of indoor

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environments. This article focuses on IAQ sensing, covering the pollutants which can currently be measured (PM or gaseous pollutants) by the real-time sensors, the state of the art in IAQ sensor technology; opportunities and challenges in their application in the field; the regulatory context; the extent of awareness of the risks and finally the public and scientific community acceptance of the need for IAQ management. Further, the health benefits brought about by IAQ sensing, compared to the traditional way of monitoring, are critically evaluated, and the directions for future research to fill any identified research gaps are suggested.

2. Key issues for IAQ monitoring

The quality of the inhaled air can affects human health (Jones, 1999). Considering that the majority of our time is spent indoors, knowing the quality of the air in buildings is therefore of increasing importance for assessing the involved risks. In older buildings that are not airtight, IAQ follows the quality of the outside air. Changes in the building regulations for improving energy efficiency over the past decade have led to modern buildings that are more airtight than older ones. These improvements have led on the one hand to more comfortable houses and offices with lower running costs, but on the other hand they have resulted in indoor environments in which air pollutants can be readily produced and build up to much higher concentrations than those found in the atmospheric environment.

Indoor air pollutants can be emitted from a range of sources (Lai et al, 2004). The most important for older buildings are combustion for heating, tobacco smoke, cooking as well as VOCs emitted from materials used indoors (Colbeck and Zaheer, 2010). For constructions built from the beginning of the 19th century until the late 1980s, material deterioration and exposure to asbestos is another important risk factor. For modern constructions pollutants coming from building materials, including VOCs emitted from paints, varnishes, and preservatives, are of greater concern (Wolkoff, 2013). Finally, insoluble nanoparticles (i.e., those with diameters smaller than 100 nm; Kumar et al., 2013b) as well as biological particles present in the indoor air can also affect human health through direct toxicity, immune mechanisms, and infectious processes.

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IAQ also can cause the Sick Building Syndrome (Sundell et al, 1994), where dwellers exhibit a range of health effects that are related to the time they spend indoors. However, determining the key pollutants responsible for the sick building syndrome (UN, 2013) is challenging mainly due to the limitations in IAQ monitoring (Sections 3.1-3.3), making causality difficult to establish causality. In fact, our understanding of the health risks from indoor air pollution is far less compared to that of outdoor pollution. This imbalance needs to be corrected by developing appropriate sensors and involving the broader community for their use.

The other important issue for IAQ monitoring is the standardisation of regulatory values for which monitoring are required. Guidelines are certainly needed and although the same gaseous pollutants are present outdoor and indoor the concentrations might be higher in the latter case and exposure time for humans due to the risk for adverse health effects should also be taken into account. For this reason, it is normal to have different monitoring strategies and limit values for outdoor and indoor air (Fioravanti, 2016). In Table 1, we summarise those limits for different pollutants (EU, 2008; WHO, 2010; Settimo and D'Alessandro, 2014). It should be taken into consideration that the WHO Air Quality Guidelines are based on 2005 global update (WHO, 2006) for outdoor air and for the indoor air on the World Health Organisation (WHO) guidelines for selected pollutants (WHO, 2010). The same table also shows the European Union (EU) reference values for ambient air according to the 2008/50/EC Directive (EU, 2008). For PM_{10}, the daily limit value is considered more stringent although WHO recommends an annual averaging limit that might take precedence over the daily value. It should be also mentioned that for certain pollutants EU legislation allows a limited number of exceedance, which are not taken into consideration in the compilation of Table 1. Also for outdoor benzene and benzo[a]pyrene, WHO guidelines have not proposed specific reference values. The values for these pollutants shown in Table 1 are estimated values based on the assumption of lifetime risk of 1×10^{-5}. It is evident from this table that indoor and outdoor monitoring process is subject to diverse monitoring and averaging requirements that make selection of a single sensor or monitoring device rather complicated systems and the telematics process of registering the measurements is suitable for big data transmission that can be affronted only with modern wired and wireless

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telecommunication infrastructures.

Table 1. Comparison of outdoor and indoor reference values for air quality monitoring. The recommendations are based on EU (2008) directive for Clean Air and the WHO (2010) guidelines for selected pollutants for indoor air quality. The averaging period for each pollutant is shown in the brackets; "NA" refers to not available.

Pollutants	Indoor Air	Outdoor Air
Formaldehyde (μg m^{-3})	100 (30 minutes) WHO	NA
Naphthalene (μg m^{-3})	10 (1 yr) WHO	NA
Trichloroethylene (μg m^{-3})	Carcinogenicity with risk of 4.3×10^{-7} per concentration unit, WHO	NA
Tetrachloroethylene (mg m^{-3})	0.25 (1 yr) WHO	NA
PAH (Benzo[a]pyrene; ng m^{-3})	All indoor exposures relevant to health, lung cancer with risk of 8.7×10^{-5} per concentration unit, WHO	1 (1 yr) EU; 0.12 (1 yr) WHO
CO (mg m^{-3})	100 (15 min) WHO, 35 (1 hr) WHO, 10 (8 hr) WHO, 7 (24 hr) WHO	10 (max daily 8 hr mean) EU; 30 (1 hr) WHO, 10 (8 hr) WHO
NO_2 (μg m^{-3})	200 (1 hr) WHO; 40 (1 yr) WHO	200 (1 hr) EU/WHO; 40 (1 yr) EU/WHO
C_6H_6 (μg m^{-3})	No safe level of exposure recommended risk of leukaemia estimated as 6×10^{-6} per concentration unit, WHO	5 (1 yr) EU; 1.7 (1 yr) WHO
O_3 (μg m^{-3})	NA	120 (max daily 8 hr mean) EU; 100 (8 hr) WHO
PM_{10} (μg m^{-3})	20 (1 yr) WHO; 50 (24 hr) WHO	20 (1 yr) WHO; 50 (24 hr) WHO; 40 (1 yr) EU; 50 (24 hr) EU
$PM_{2.5}$ (μg m^{-3})	10 (1 yr) WHO; 25 (24 hr) WHO	10 (1 yr) WHO; 25 (24 hr) WHO; 25 (1 yr) EU

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3. State of the art in IAQ sensing

Typically, for compliance with ambient air quality regulations, measurements of carbon monoxide (CO), sulphur dioxide (SO_2), ozone (O_3), oxides of nitrogen ($NO + NO_2$), benzene (C_6H_6) and VOCs, together with PM_{10} and $PM_{2.5}$ are conducted (Rickerby and Skouloudis, 2014). Yet, regarding indoor environments, a variety of human activities and emission sources require hydrocarbons, other volatile species and/or particle number concentrations (PNC) to be taken into account.

Although conventional analytical instruments can be used to accurately measure the concentration of the above listed pollutants found in the indoor environment, they are not practical because of the following reasons. Firstly, they are bulky, and in many cases noisy, making them inappropriate for indoor use. Secondly, they are expensive to install and complicated so their operation requires experienced personnel. Finally, the accuracy of these instruments, in most cases, is excessive for the needs of IAQ monitoring where the objective is to have a screening tool to evaluate whether the concentration of certain pollutants exceeds some threshold values. This requirement, together with current market demands for IAQ sensors, has motivated researchers to develop battery-operated low-power devices that can be readily employed.

Recent advances in air sensor technologies have led to the emergence of a number of hi-tech air sensing devices (Kumar et al., 2015; Snyder et al., 2013), capable of measuring a range of common indoor air pollutants such as VOC, CO, O_3, NO_2, SO_2 and PM. For indoor air sensing, ideally the devices must have good response times, exhibit high performance, be robust and vandal proof (Mead et al., 2013). These devices are becoming compact, light-weight and inexpensive (up to US $500) (Holstius et al., 2014). In fact, some of the most recent devices (e.g., Atmotube) are available for less than US $100 (Atmotube, 2016), although these limit concentration measurements to gaseous pollutants such as CO, benzene and VOCs. Most emergent air sensors come with additional enhanced technical and performance features that include: low-power consumption, light-weight, an acceptable level of efficiency, sensitivity and selectivity. A good number of these sensors are battery-operated,

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mobile, and wearable; and have communication protocols incorporated in them that allow data to be transmitted via Bluetooth or Wi-Fi to a remote platform such as PC or smartphone for viewing, with the help of application software (White et al., 2012). Owing to continual technological improvement in detection capabilities, it is becoming common that air sensors can detect a number of criteria pollutants. However, many of them are pollutant-specific, such as NGD8800, which senses mainly methane and VOCs.

Air sensing devices have built-in microelectromechanical systems (MEMS) made using micro-fabrication techniques (Snyder et al., 2013). MEMS are transducers smartly interfaced to microprocessors with electronic circuitry (Kumar et al., 2016). Transducers respond to environmental changes with corresponding physiochemical changes, and these properties are harnessed to generate electrical pulses that are processed to signals and converted to digital data with the aid of microprocessors and analogue-to-digital converters (Snyder et al., 2013). MEMS transducers come in different chemical composition, shape and size, and are either microfluidic, optical, gas or nanomaterial-based.

3.1 Gas sensors

Gas sensors measure the concentration of gaseous species by analysing reactions between the sensing material and target gases and presenting the outcomes as electrical pulses or signals (Xiang et al., 2013). The operating principles of solid-state gas sensors are typically based on changes of the electrical properties of thin films made of a semiconducting material (Ho, 2011). These sensors commonly employ n-type semiconductors whose conductivity is very sensitive to their uppermost "surface depletion" layer, which is typically nanostructured for improving sensitivity (e.g., Isaac et al., 2016). Once the target gas adsorbs on, or desorbs from the semiconductor surface, it captures or releases electrons and therefore changes its conductivity (Guidi et.al., 2012). The sensitivity of these films is proportional to the number of surface-active sites that are available for the target gas to adsorb and to their surface-to-volume ratio, and therefore the efforts, up to now, have focused on doping and nano-structuring them (Gaury et al., 2013, 2014; Nicoletti et al., 2003). Also, sensors that rely on optical changes of metallic thin films have been proposed (Isaac et al., 2015), but these are

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primarily meant for sensing hydrogen molecules that penetrates the thin films and changes their optical properties. Another example is the commercially available hydrogen sulphide sensors that can reliably measure very low workplace concentrations with a high resolution (RibbleEnviroLtd., 2015).

Although the concentration of typical gaseous pollutants (e.g., NO_2, O_3, CO) could be measured using arrays of solid-state gas sensors as described above, reliable detection of indoor VOC requires a higher degree of selectivity. This is because: (i) most of the VOCs in indoor environments are at relatively low concentrations, and (ii) a few of them (e.g., benzene, formaldehyde) are highly toxic (Granqvist et al., 2007). There have been advances in this direction, and for example, Zampolli et al. (2005) developed a miniaturized gas chromatographic (GC) system for monitoring single volatile compounds in indoor air. The system consisted of a micro-machined packed GC column for classifying the VOCs and a metal oxide gas sensor for the detection. Using this system, they managed to detect hazardous pollutants such as benzene in air at concentrations down to 5 ppb. However, the sensors that are capable of detecting and quantifying even lower levels of these pollutants are still to be developed.

One of the limitations of some types of gas sensors is that they may suffer from short life-time. However, the commercially available non-consumptive and lead-free sensors for measuring oxygen are characterised by a particularly long service life of more than 5 years, and therefore can be safely incorporated in modern indoor monitoring infrastructures in public and private indoor environments (Honeywell, 2014; RibbleEnviroLtd., 2015). Such sensors can be installed in fixed or mobile locations indoor and can operate with either normal power supply or under emergencies with alkaline batteries or with rechargeable Nickel Metal Hydride (NiMH) batteries. Nowadays, the latter enable a reliable power supply for more than 12 hours, and with the high capacity battery pack, for more than 13 hours (EBM, 2010). Depending on requirements, the batteries can be charged from the in-house electric power supply or from a vehicle.

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3.2 Particle sensors

In general, measuring PM is more challenging because, apart from the concentration, information about the size and other characteristics of the airborne particles are also important for determining their impacts on human health. Traditionally, PM concentrations are measured by offline gravimetric methods or near real-time attenuation techniques (Triantafylou et al., 2016). One method for online particle mass measurement is to use a sensor with a piezo-crystal which vibrates proportionally to the mass of particles deposited on it (Snyder et al., 2013). Particle monitoring can be more efficiently achieved by optical techniques including optical particle counters (OPCs) employed since the early 60s, and the newest types are significantly reduced in the size making them portable (Burkat et al., 2010). These instruments measure the light scattered by the sampled particles in order to determine their number density, which is converted to PM mass concentration by assuming a mean particle density. Depending on the validity of this assumption, the error in PM measurements using an OPC could be as high as 100%. In view of the increasing demand for IAQ, new passive (i.e., without needing pumps and flow systems to sample air), portable and cost-effective OPCs have been developed (Northcross et al., 2013).

A major limitation of OPCs, including the new generation of portable instruments, is that they only detect particles larger than the wavelength of visible light (of the order of a few hundred nm). Although detecting smaller particles is not important when expressing PM pollution in terms of mass concentration, it is of critical importance when the focus is on PNC (Kumar et al., 2010). Concentration of particles smaller than a few hundred nm can be measured using Condensation Particle Counters, CPC (Northcross et al., 2013), which are OPCs coupled with saturator-condenser to grow particles by condensation to micron size droplets. The accuracy of these instruments in determining the particle number concentration is within less than 20%, but similarly to the OPCs, when mass concentration is required assumption of a mean particle density has to be made, which can lead to large errors. Although CPCs have been the primary instrument for measuring PNCs over the past decades (Flagan, 1998), they have neither been miniaturized nor made sufficiently cost-effective to allow their use in IAQ. The most efficient way to detect and size submicron airborne particles is by using electrical mobility techniques.

The most widely used electrical mobility classifier is the Differential Mobility Analyzer (DMA) introduced by Knutson and Whitby (1975). Despite the wide range of DMA designs introduced, little attention has been paid to other practical aspects, such as reducing the size, weight and cost of these classifiers, thereby making them more suitable for particle distribution measurements. This limitation was recently overcome by Barmpounis et al. (2016) who developed a cost-effective and lightweight DMA. In the same direction, Bezantakos et al. (2015) introduced a novel electrostatic precipitator that can be used as an efficient aerosol particle segregator. These novel classifiers will certainly allow the production of less expensive instruments for sizing airborne particles in the coming years, without sacrificing the accuracy in particle sizing compared to conventional classifier (which is ca. 3%). Finally, particle counters based on the principle of corona charging are also currently available on the market. Even though their size and time resolution are adequate for IAQ monitors, their cost still does not meet the requirements for large-scale deployment.

For assessing their effects upon human health other particle characteristics such as morphology and chemical composition are also important. However, this requires more elaborate systems which are currently used purely for research purposes. As a result, there are hardly any "small" versions of such instruments available that could qualify as sensors useful for IAQ exposure.

3.3 Packages of sensors

The majority of packages of sensors cannot provide reliable information, since they still have limitations regarding their selectivity (Castell et al., 2014). However, by using an array of them in a stand-alone package (sometimes referred to as an electronic nose; e-nose or node) along with pattern recognition algorithms, they have been shown to work efficiently for air pollutants typically found in indoor environments (Sohn et al., 2002). For instance, Zampolli et al. (2004) developed an e-nose (based on semiconductor metal oxide gas sensors) capable of identifying and quantifying the concentration of CO and NO_2, which are used as air quality proxies and hence the most monitored pollutants.

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Technology advances currently allow the simultaneous detection of between 1 and 4 combustible gases (e.g., methane, propane) and vapours (e.g., ammonia, benzene), as well as O_2, CO, NO_2, SO_2 and H_2S by using electrochemical sensors (RibbleEnviroLtd., 2015). Reliable and fully mature measuring technologies incorporate durable detectors that are easy to handle and guarantee a high degree of safety with low operating costs (RibbleEnviroLtd., 2015). The threshold concentration of every detector can be set for each gas enabling safe use in industry, mining and in refineries.

Recently, an integrated sensor system for indoor applications allowing explosive gas leak and fire detection, and IAQ has been developed (Schütze, 2015). In such systems, trace levels of hazardous VOCs in indoor air are detected and identified through metal oxide sensors used in temperature cycled operation (Leidinger et al., 2014). Other examples of IAQ sensors include the PACMAN sensor developed by NIWA Ltd. that were specifically devoted to particulate and CO_2 monitoring (NIWA, 2015); IAQ sensing systems are being developed through recent initiatives such as IAQ Sense (2015), Roomba for formaldehyde detection (Roomba, 2015), crowd-funded sensor network such as Atmotube (2016) and numerous other efforts by individual groups (Abraham and Li, 2014; Bhattacharya et al., 2012).

In order to show the conditions under which sensors are required to operate, Table 2 summarises the range of measurements for each pollutant, the detection limits and the EU limit values as well as the averaging period. This table is a product of many years of industrial development and deployment of sensors (Carotta et.al, 2007) with contracts from Pirelli & C. SpA (2003-2006), Orion SRL (since 2000), the Joint Research Centre (since 2013) and EU funded project on Advanced Distributed Architecture for tele-monitoring services (IST-2000-28452, since 2000) and the broad literature. The limit values are according to EU regulations for outdoor monitoring taking into consideration the most stringent criterion for each pollutant. In order to characterize the uncertainty of sensor measurements, the same table describes the precision as a percentage of the value at the full scale. This uncertainty is derived from the standard deviation of the mean value following repeated measurements under the same conditions.

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Table 2. Specifications of the metal oxide sensors for detection of pollutant gases. PM values are from measurements with orthogonal light scattering. Precision is defined as the standard deviation of the mean value of a set of repeated measurements under the same conditions expressed as percentage of the full scale (f.s.) value.

Pollutants	Measuring range	EU limit value (averaging period)	Detection limit	Precision
CO	0-100 mg m^{-3}	10 mg m^{-3} (maximum daily 8 hr mean)	0.1 mg m^{-3}	0.1% f.s.
C_6H_6	0-200 μg m^{-3}	5 μg m^{-3} (1 yr)	0.2 μg m^{-3}	0.2% f.s.
NO_2	0-500 μg m^{-3}	40 μg m^{-3} (1 yr)	10 μg m^{-3}	1% f.s.
O_3	0-500 μg m^{-3}	120 μg m^{-3} (maximum daily 8 hr mean)	20 μg m^{-3}	2% f.s.
PM_{10}	0-400 μg m^{-3}	50 μg m^{-3} (24 hr)	1 μg m^{-3}	< 2% f.s.
$PM_{2.5}$	0-400 μg m^{-3}	25 μg m^{-3} (1 yr)	1 μg m^{-3}	< 2% f.s.
PM_1	0-400 μg m^{-3}	not applicable	1 μg m^{-3}	< 2% f.s.

4. The challenges: monitoring design and data utilisation

Air sensors provide novel ways to assess and characterize environments qualitatively and quantitatively in terms of pollution, and human exposure. More specifically, air sensors offer a rare opportunity to assess air quality of indoor environments in real-time (Mead et al., 2013). Most IAQ sensors, with installed communication protocols, are able to detect and transmit data in real-time to digital platforms, e.g., to a server, PC or smartphone, which in turn broadcast the data to a designated web portal for real-time analysis and visualization. The performance characteristics of a sensing device are the determining factors for its suitability as an indoor air monitor. When the high quality of the sensor data can be ensured (which at

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present is frequently not the case), the availability of real-time and online pollutant measurements offers a wide range of possibilities of improving the air quality of indoor environments and associated effects on human health. Examples of these are the identification and quantification of emissions from acute or chronic pollutant sources, the characterisation of emission patterns in order to implement mitigation strategies, and the optimisation of indoor/outdoor air exchange rates to minimise pollutant loads while increasing energy efficiency, among others. From a citizen engagement perspective, access to high-quality yet lower-cost indoor air pollutant data would promote monitoring in increasing numbers of indoor environments and raise awareness on this environmental and public health issue.

Electronic sensors have been used for several decades as detectors of hazardous indoor gases (e.g., detecting the leakage of gas from household appliances, liquefied petroleum and compressed natural). Similar, to the sensors described in Section 3, these detectors give an electric signal upon interaction of the analyte (the gas in question) with the sensing material. When the detected gas density reaches a threshold value, the corresponding electric signal triggers an alarm alerting users that the concentration of a specific gas is above safety limits. Sometimes such releases are coupled with intelligent household electronic systems triggering emergency call actions, or relaying the local conditions to competent teams or authorities responsible for safety hazards (Honeywell, 2014).

Although the monitoring technologies, discussed above, are primarily designed for safety and alerting of hazardous gases, they are well advanced. However, the same is not the case for monitoring the exposure of the population to outdoor and indoor atmospheric pollution or for monitoring indoor occupational hazards. The issues associated with such monitoring are two-fold. Firstly, several sensors with different operating principles are required for conventional pollutant monitoring, and this imposes power consuming restrictions which renders them unsuitable for mobile application. This is of particular importance considering that these sensors need to relay their data via wireless networks in centralised monitoring systems. Secondly, such units should be capable of detecting concentrations that are substantially lower than the outdoor levels, with significantly less temporal variability than the 1-2 seconds, which is usually the sampling requirement for outdoor monitoring to capture peaks in concentration.

One of the important considerations for the sensing protocols is the sampling/averaging frequency for monitoring, and the compromises that may have to be made in this regard. It is well known that mean values on an hourly or daily basis completely obscure the presence of shorter duration peak concentrations, and therefore, are suitable only for assessment of the average levels of exposure (Skouloudis, 2000). Such averaging periods are suitable for populations that do not move about a lot and are not exposed to workplace hazards of different pollutant levels, i.e., for children or for immobile elderly (Skouloudis, 2007). For the majority of the population, peaks in concentration that may be associated with acute health effects are required to be taken into account. Whilst several of these effects have been proposed, they are not adequately quantified (e.g., asthma attacks or cardiovascular episodes). Peak concentrations are most pronounced in the proximity to the generating air pollution sources, and therefore pose a risk to those present in such environments, e.g., taxi drivers, or anybody directly exposed to traffic emissions (Goel and Kumar, 2015; Joodatnia et al., 2013). As an example, such types of peaks are shown in Figure 1 for NOx and CO at two separate heights at Palazzo Mellini Fossi in Florence (Italy), just outside the windows of a historic building alongside a busy street canyon (Skouloudis and Kassomenos, 2014). Studies to quantify peak concentrations and exposures cannot be conducted with passive samplers, which impose broad temporal integration, or with conventional monitoring stations, which are limited by the number of sampling sites and potentially by a too coarse time resolution.

Another essential consideration in IAQ monitoring is the positioning of the sensors for obtaining accurate real-time measurements. For characterising the indoor air pollution, the limiting factor is that the reliable sensor units are not always mobile due to the need to be connected to a power source. In addition, it is not always feasible to propose that the devices are carried by citizens as handheld smart devices because these are rather expensive at this stage.

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An important consideration is the difficulty in interpreting the readings from the sensors and ‘translating’ them into IAQ management actions. The ability to do this usually rests with air quality experts, but not with the building managers or the community. One way to achieve this is with the aid of visual signals, but this place the requirement that the sensor system not only records and displays the readings, but also conducts some level of computation.

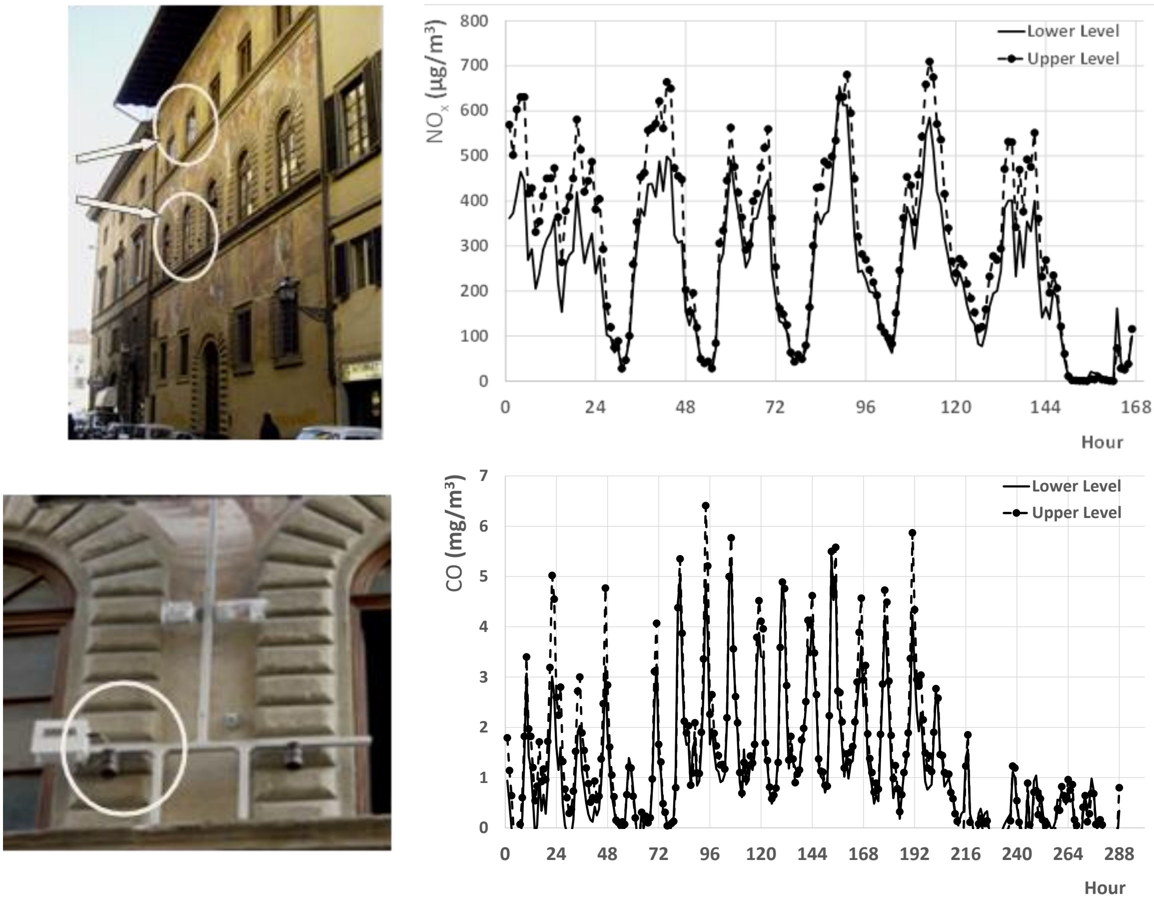

Figure 1. Monitoring in two different lower (6 m) and upper (12 m) levels at Palazzo Mellini Fossi in Florence, Italy (Skouloudis and Kassomenos, 2014).

5. Potential benefits of IAQ sensing compared with traditional monitoring

In IAQ studies, health impact assessments have frequently been carried out by means of passive samplers, placed at fixed locations in rooms where high concentrations were expected, or carried by volunteers, especially when integrated doses for occupational hazards were to be assessed. As discussed in Section 4, the main limitation is that in both cases the reading is integrated over time (from several hours to several days), and do not reflect spatial variation of pollution concentration. Sensors with direct readings promise to open up a new era in high resolution of spatiotemporal IAQ sensing, and at the same time empower individuals to control their own environments. The expected benefits from this new approach cover a number of aspects.

- *Real-time characterisation of indoor concentrations, which may then be compared with values recommended by guidelines, e.g., WHO guidelines (WHO., 2006; WHO., 2009) or prescribed standards:* As discussed in Section 4, real-time monitoring would aid health risk assessments by providing data on peak concentrations (acute exposures) which are otherwise frequently hidden under longer averaging time periods.
- *Increased spatial resolution:* Because of the transient nature of most indoor emission sources, the large spatial and temporal variation of pollutant concentrations is a key issue to be taken into consideration in exposure and risk assessments. Whereas conventional instruments are unable to capture this spatial variability due to the low number of units deployed, the use of indoor sensing devices will largely increase data availability on smaller spatial scales, thus improving the robustness of risk assessments. However, it should be noted that this increase in data coverage, also, will increase the need for skilled staff to process and interpret the data into useful information.
- *Reduced uncertainty:* Given that monitoring at an increased number of locations will become possible, the use of low cost sensor technologies will allow uncertainties linked to the effect of measurement location on the variation of pollutant concentrations to be avoided (Ciuzas et al., 2015).
- *Identification of emitting sources from indoor activities:* As a result of the increased spatial resolution, it will be possible to target specific sources by monitoring associated pollutant emission processes. This will be particularly useful in developing countries (e.g., cooking stove emissions), but also in developed countries with regard to residential heating (e.g., open gas fires, kerosene heaters, biomass boilers; Hanoune and Carteret,

2015), among other sources. Furthermore, source apportionment analyses of indoor pollutants (e.g., VOCs) may become possible (Poulhet et al., 2015).

- *Air data supply:* Providing data on pollutants not frequently monitored in indoor environments, such as formaldehyde, VOCs, benzene or PNCs in indoor air, as well as discomfort and heat stress may become possible using indoor sensing devices. In addition, other parameters such as dynamic characteristics of pollutants, needed to improve management of IAQ (Ciuzas et al., 2015; Yu et al., 2013), may also become available using sensor technologies.
- *Improved IAQ management:* indoor sensing technologies will improve IAQ management, which implicitly will improve indoor population health outcomes. The increased spatial and temporal coverage provided by sensor technologies as opposed to conventional instrumentation will favour the more rational and optimised management of ventilation strategies, preventing wrong decisions and subsequent adverse effects on health (Kim et al., 2014).
- *Health benefits:* By lowering the cost of air-pollution monitoring, sensor technologies will facilitate fundamental understanding of health impact and allow assessments that were not possible with conventional devices. This will specifically benefit low-income households, for which indoor comfort, IAQ, health, and energy and environmental problems were recently assessed (Kolokotsa and Santamouris, 2015).

6. Regulations and awareness

There are several indoor environment parameters which are regulated by most of the developed countries, and include indoor temperature range, relative humidity (RH) and carbon dioxide (CO_2). Temperature and RH relate to thermal comfort, while CO_2, a by-product of the natural human metabolism, increases in concentration in indoor spaces which are inadequately ventilated in relation to the number of occupants of these spaces thus leading to decreases in the level of humans' performance (Satish et al., 2012). All three of these parameters may be already monitored by a wide range of advanced sensor technologies. It is noteworthy that it is very clear how to interpret the readings of these sensors, and what

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corrective actions to take if the measured parameters are outside the desirable levels, such as heat or cool the space if the temperature is outside the desirable range and ventilate in case of high CO_2 levels. In some German schools, for example, the indoor CO_2 status is indicted visually by 'traffic lights': green (within the range), yellow (on the boundary), red (above the range, which means windows need to be opened). Thus, sensor technologies and their applications are mature for RH, T and CO_2.

However the same cannot be said in respect of a wide range of indoor air pollutants which have significant implications on health. This was recognised by the WHO by issuing a set of health guidelines for concentration levels of indoor pollutants considered as health risk (WHO., 2009). For several pollutants, including particulate matter ($PM_{2.5}$ and PM_{10}), CO, O_3, lead and SO_2, the same numerical health guidelines apply to both outdoor and indoor environments (WHO., 2006). Guidelines for IAQ (WHO., 2009), cover indoor pollutants including: benzene, CO, formaldehyde, naphthalene, NO_2, polycyclic aromatic hydrocarbons, especially benzo-[a]-pyrene, radon, tetrachloroethylene and trichloroethylene. While both CO and NO_2 are already included in the WHO Guidelines for Air Quality (WHO., 2006), their inclusion also in the Indoor Guidelines was due to the different nature of exposures to these gases in indoor environments. In addition, guidelines on two other categories of health risk in indoor environments also, were recommended namely biological agents and indoor combustion of solid fuels. The WHO guidelines on dampness and mould recommended control of dampness, as it is due to water ingress/leakage and inadequate ventilation such that many biological agents are present in the indoor environment (WHO., 2009). The question is however, whether these guidelines are used for regulating IAQ by national legislation bodies. While it is outside the scope of this paper to review national regulations in relation to IAQ, and while there are differences between countries, in general, IAQ regulations are far behind those for ambient outdoor air quality. Moreover, IAQ regulations are more complex to interpret or implement and they are not performance based (e.g., prescribing maximum concentration levels of indoor pollutants and their averaging times). Without clear standards, routine monitoring of IAQ does not take place and the availability of sensors is unlikely to change this situation. This could be illustrated by way of the example of the European Union

Directives (89/391/EEC, 1989; 98/24/EC, 1998) (IAQ EU Directives, 1989). Furthermore, it should be taken into account that the indoor monitoring with sensors technologies does not substitute the reference instrumentation required for monitoring purposes. However, traditional instrumentation is bulky and could be used only in an invasive way in typical indoor spaces. It is difficult to imagine normal human activities taking place simultaneously with the monitoring of $PM_{2.5}$, PM_{10}, CO, O_3 and SO_2 from traditional instruments. On the contrary, sensor technologies are now becoming robust as well as calibration and maintenance free, offering an opportunity to deploy them in exactly the same way as the sensors for temperature, RH or CO_2. Obviously, there might be ethical issues associated with continuous indoor monitoring because these sensors could reveal the human activities with better temporal frequencies and spatial representativeness than those obtained from traditional instrumentation. These ethical issues could be considered similar to privacy issues that emerged in the early 1990's following the introduction of mobile telecommunication. When individual citizens envisage the benefit from the deployment of such sensors the necessary adjustments could be introduced to the ethical directives that protect the privacy of individuals. The situation is particularly complex regarding residential housing. Even if there were regulations on IAQ, their implementation in residential environments would be very problematic for at least two reasons. Firstly, their enforcement would require routine monitoring in these environments, which is completely not feasible at the moment, and which would require not only much more advanced sensor technologies, but a different regulatory framework, making them mandatory, which also is also unlikely. Secondly, even if monitoring was conducted, the interpretation of the data for management would in most cases be very difficult, particularly in relation to the pollutants, which have both indoor and outdoor origin. For example, PM is generated both indoors and outdoors, and therefore, the question arises as to whether the windows should be opened to ventilate cooking or cleaning generated particles, or closed to prevent ingress of traffic particles? Such assessment is possible only by experts and there are no simple tools available as yet for building owners or the public to become engaged. Therefore, availability of data from sensors would be of limited use in this type of situation.

Perhaps even more fundamental, however, is the widespread lack of awareness of IAQ: monitoring something with a view to improve the situation, needs people to be aware that the situation poses a risk. It is not only that people are not aware of risks due to involuntary exposure to air pollution (e.g., pollution from outdoor sources penetrating indoors), but people tend to use fragrances, excessive cleaning products, candles for ambiance, and many other sources of indoor air pollutants, without understanding their contribution to IAQ problems. Therefore, firstly, much better awareness of IAQ issues would need to be developed, and secondly, tools to interpret the sensor data to enable appropriate action on the information gathered, would be necessary, also. Neither of these exists as yet, and therefore it is argued that currently available sensors are *ahead of their time*.

7. Conclusions and future outlook

Advancements in air pollution sensing promise to revolutionise IAQ monitoring and present opportunities for much improved exposure assessment, but there are still many challenges which need to be addressed, and include:

Data reliability and accuracy is of paramount importance in making use of sensor data for predicting and modelling indoor exposure, and there are many questions in this regard, which are yet to be addressed (Kim et al., 2012; White et al., 2012). In order to address these challenges, performance evaluation of emerging technologies in general and indoor sensors in particular, are being carried out by research groups across the world. Through laboratory and field testing, sensors are being evaluated against standard and benchmarked parameters in relation to sensitivity, selectivity, detectable limit, response to environmental/climatic conditions, precision and data reliability (Williams, 2014). For wearable indoor sensors, it is important that they are also tested against extreme parameters such as sensor response to human physiological changes and drift in zero and span. In as much as indoor air sensing holds the potential to improve indoor exposure assessment and contribute to better understanding of indoor pollution phenomena, there still exist real challenges.

Improving the portability and reducing the cost of sensors for measuring gaseous pollutants

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and PM without sacrificing selectivity and sensitivity is currently the main challenge in IAQ. Using arrays of stand-alone solid-state gas sensors in combination with sophisticated pattern recognition algorithms has been shown to significantly improve the selectivity of sensing devices. Improving their sensitivity, however, requires novel techniques for nano-structuring the sensing materials in a well-defined and cost-effective way.

Developing sensors for ultrafine/nanoparticle monitoring is another future requirement. Current standards for PM are based on mass, and there is already a huge debate on whether or not this is sufficient for relating particulate pollution to human health, or whether PNC should be monitored as well. Whereas specific health effects of coarse and fine particles have already been demonstrated, nanoparticles (those below 100 nm in diameter and whose mass is insignificant) travel deepest into the respiratory system and potentially are major health risk (Heal et al., 2012; Kumar et al., 2014). While sensors for coarse and fine particles are already available, albeit not always of required performance characteristics, inexpensive sensors that can measure particle number size distributions in the nano-size range are yet to be developed.

Determining the low concentration levels of gases and airborne particles and size of the latter typically requires complex measurement systems. Although novel materials have helped in reducing the weight, miniaturizing and simplifying the design of some standard aerosol instruments, there is still some way to go before appropriate tools for routine IAQ monitoring are available. It is becoming clear, however, that the use of sensor technologies for IAQ monitoring would result in higher spatially and temporally-resolved indoor pollutant data. Also, this would have clear benefits with regard to health impact assessment, given that data on specific sources, emission patterns (e.g., acute exposures) and pollutant dynamics would become available.

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the authors. Authors do not certify, endorse, or recommend any trade names and commercial products that are referred in this article.

9. Conflict of Interest

The authors declare no financial competing interests.

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